N210808 and some speculations on what it implies for IFE

LLNL IFE Workshop

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1: LLNL, 2: LANL, 3: LULI, 4: LLE, 5: GA, 6: MIT, 7: SLAC, 8: AWE, 9: DM

LLNL-PRES-829367

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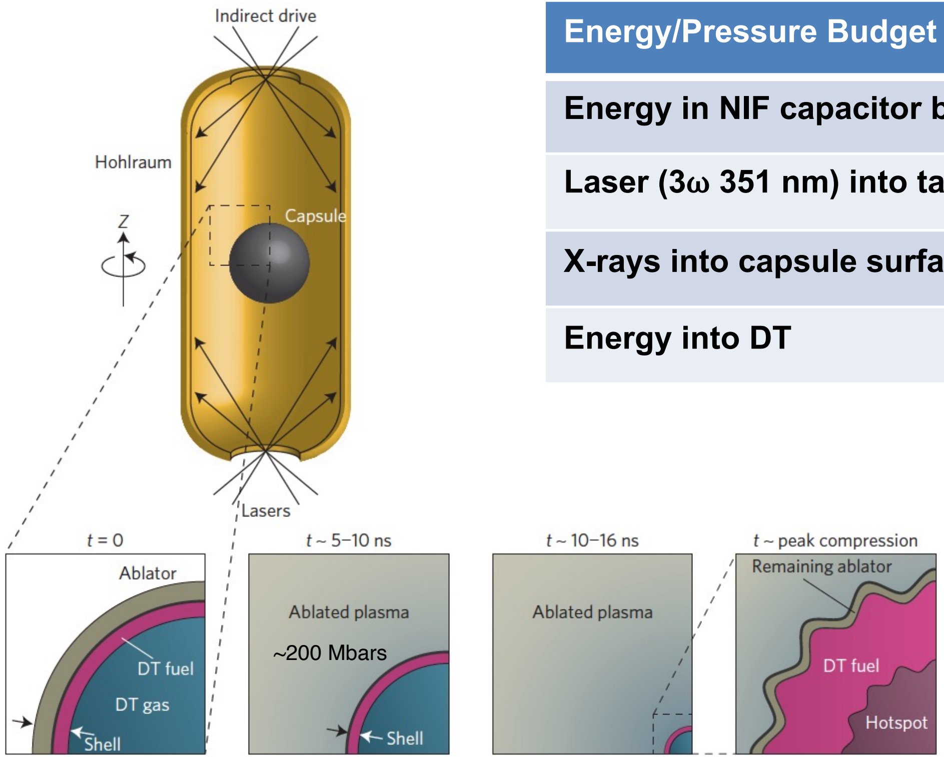
Lawrence Livermore National Laboratory

N210808 is an "existence proof" that ignition in the laboratory is possible, but getting ignition has been extremely difficult

- N210808 is the first NIF shot to achieve $G_{capsule} > 5$, (Fusion energy/capsule absorbed energy)
- N210808 appears to meet several scientific definitions of 'ignition', defined as the tipping-point of thermodynamic instability, and obtained some burn propagation
- The shot achieved $G_{target} \approx 0.7$ (Fusion Energy/Laser Energy)
  - "Scientific Breakeven" when $G_{target} = 1$
  - Real Breakeven (more energy from fusion than what is consumed by facility) on NIF not possible, but NIF was not designed for energy production
- Lessons learned:
  - Symmetry control, stability control, and high compression all more difficult than originally envisioned
  - More sensitivity to target quality and laser delivery than originally envisioned
  - Higher energy has been more useful than high peak power
  - *Optimism is not a strategy*

Indirect drive is energy inefficient, but we are trading energy for *energy density* since implosions act like "pressure amplifiers"



Betti & Hurricane, Nature Phys. (2016)

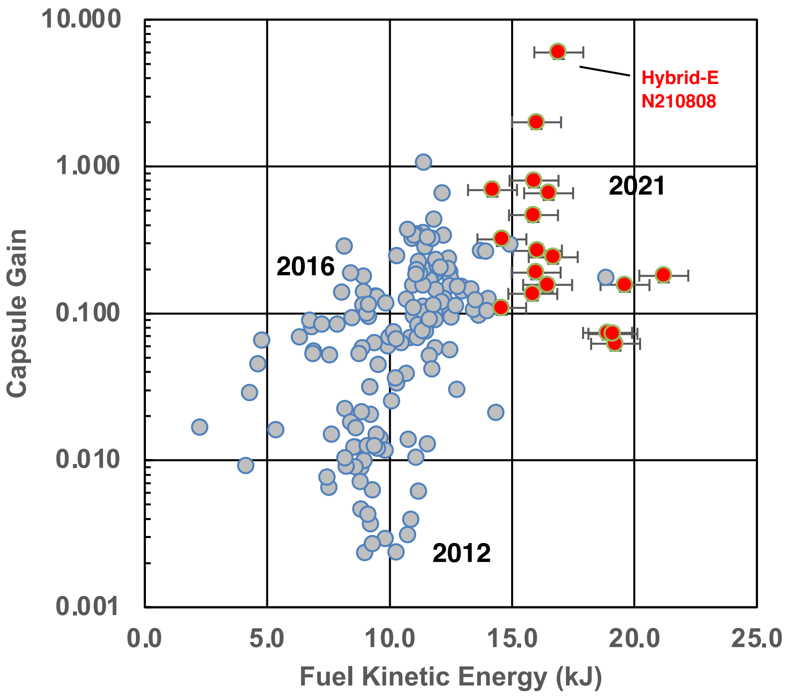
~200 Gbars

Energy/Pressure Budget for NIF	Energy	Pressure
Energy in NIF capacitor banks	300-400 MJ	
Laser (3ω 351 nm) into target	1-1.9 MJ	
X-rays into capsule surface	150-250 kJ	100-200 Mbar
Energy into DT	10-20 kJ	100-550 Gbar

The dramatic loss in energy at different stages of ICF operation leads to several different definitions of Gain:

- $G_{engineering}$ = fusion yield / facility energy
- G_{target} = fusion yield / laser energy
- $G_{capsule}$ = fusion yield / capsule absorbed energy
- G_{fuel} = fusion yield / energy delivered to DT

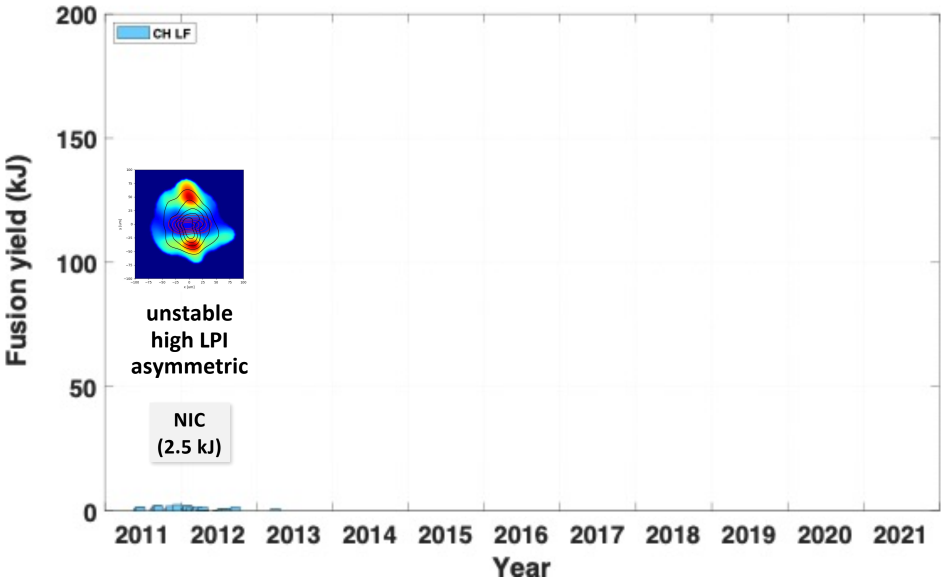
For the first time in the laboratory $G_{capsule} \gg 1$ and $G_{target} \sim 1$



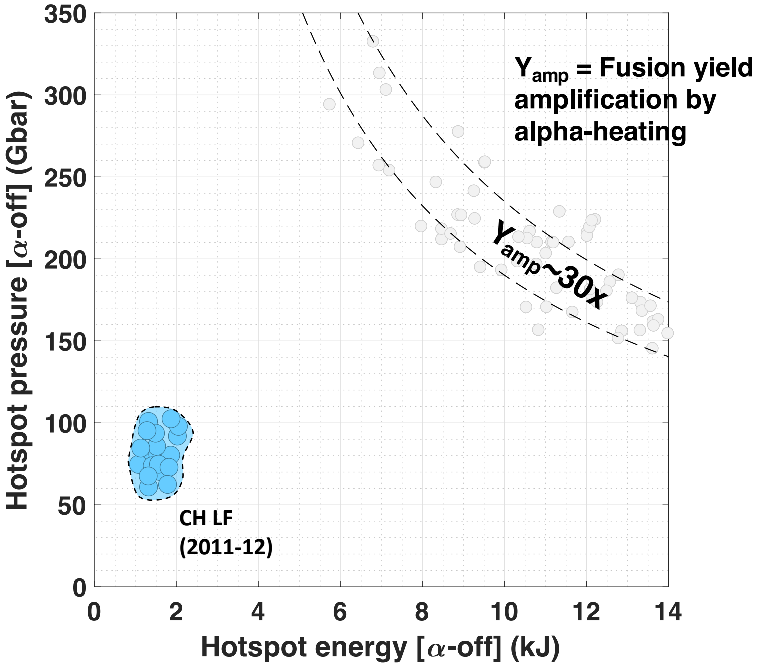
Recent fusion energy gains

Gain	N210207	N210307	N210808
G_{fuel}	7.8 ± 1.0	6.2 ± 0.9	70 ± 7
$G_{capsule}$	0.75 ± 0.05	0.57 ± 0.04	6.0 ± 0.2
G_{target}	0.09	0.07	0.7

By addressing problems *in steps* and using a basic principles understanding, we've gone from 1.5 kJ to 1.3 MJ fusion yield



Ignition figure of merit ~ $(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



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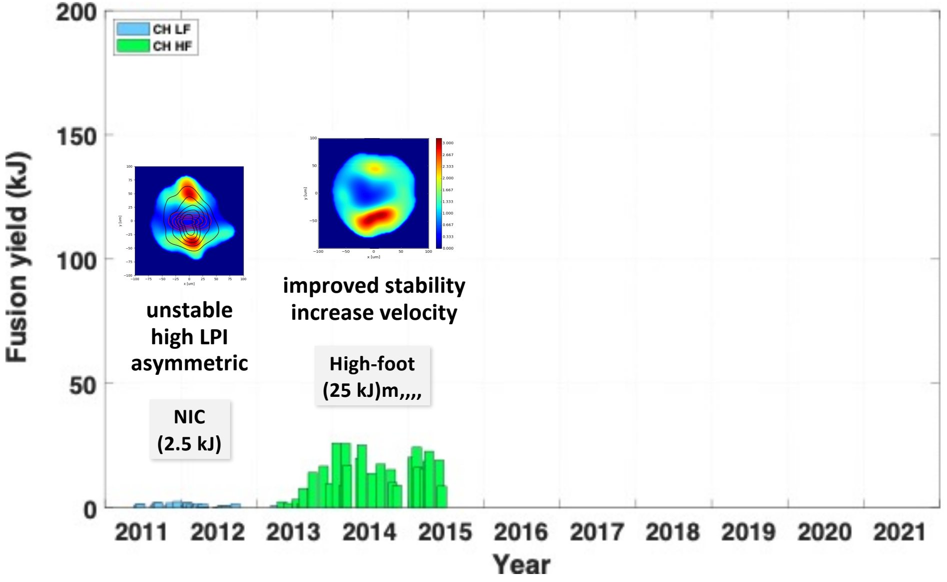

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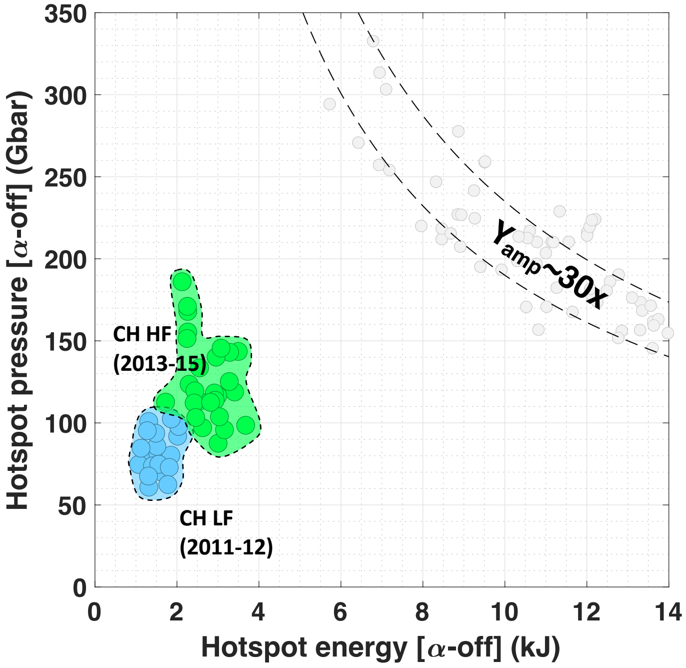

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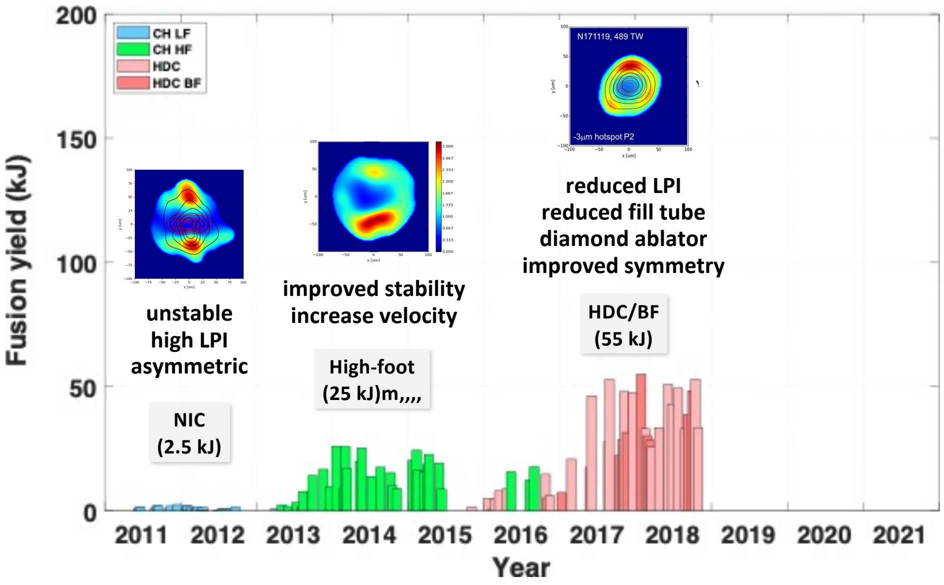

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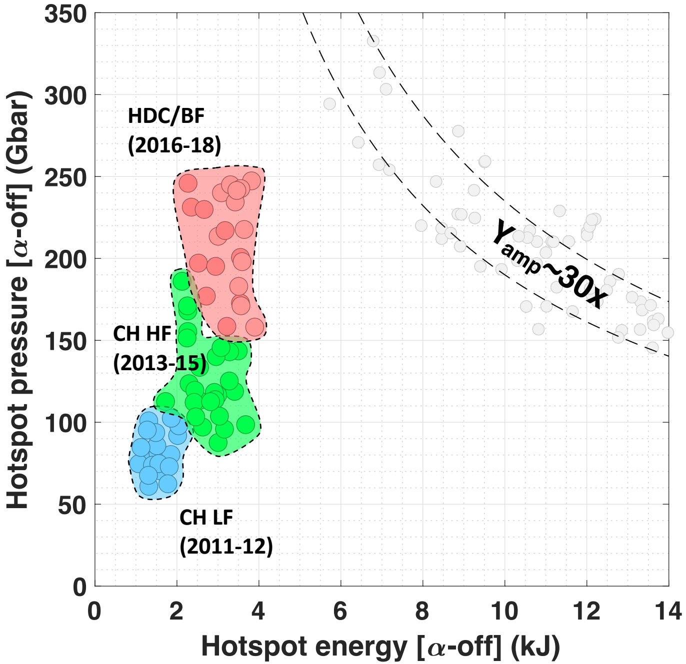

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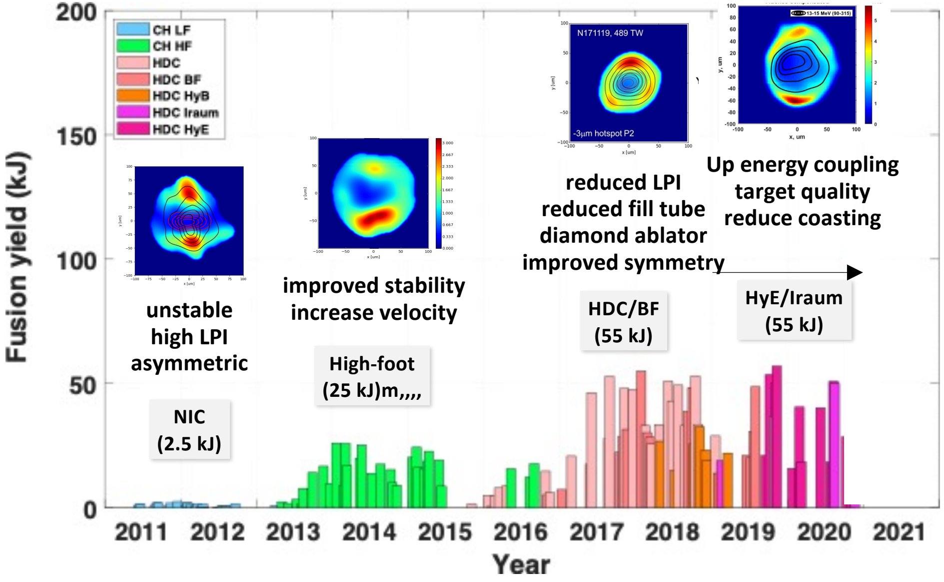

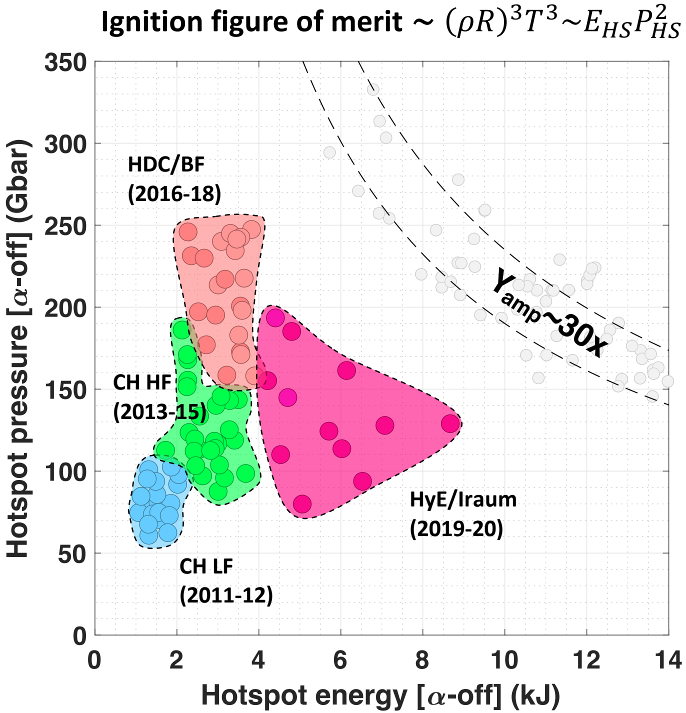

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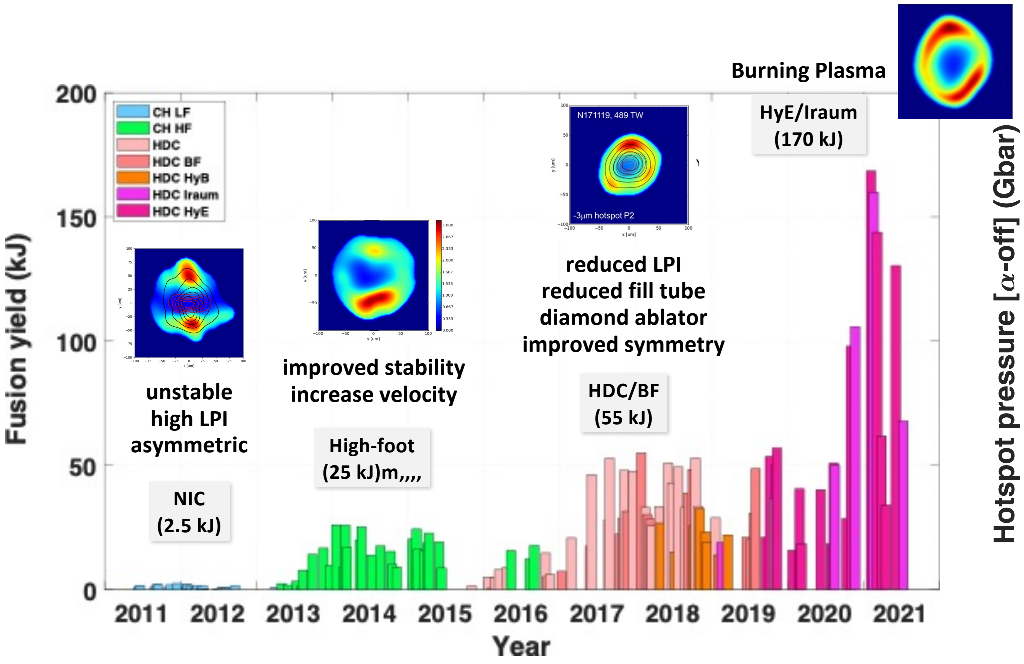

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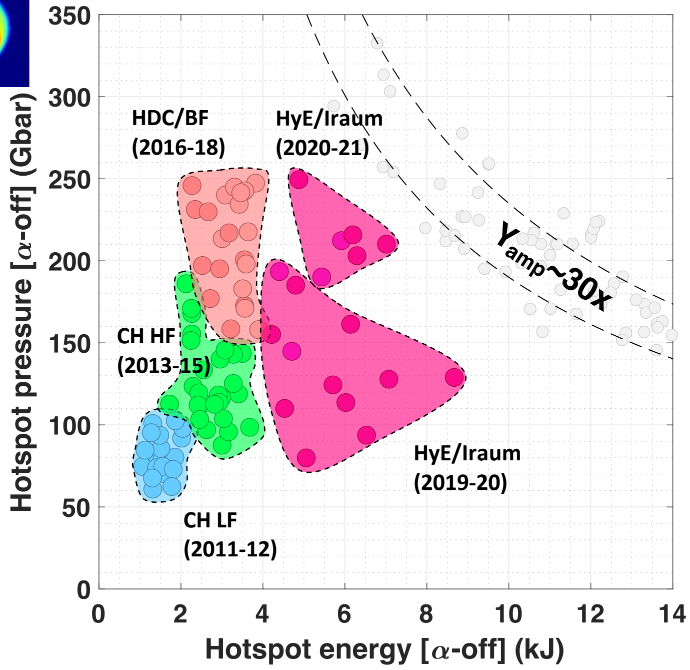

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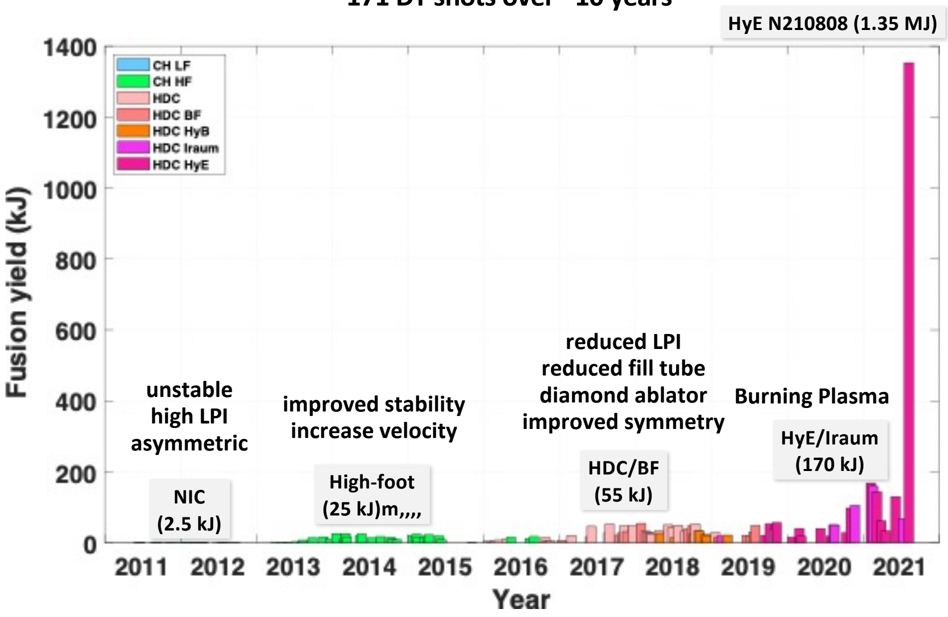
171 DT shots over ~10 years



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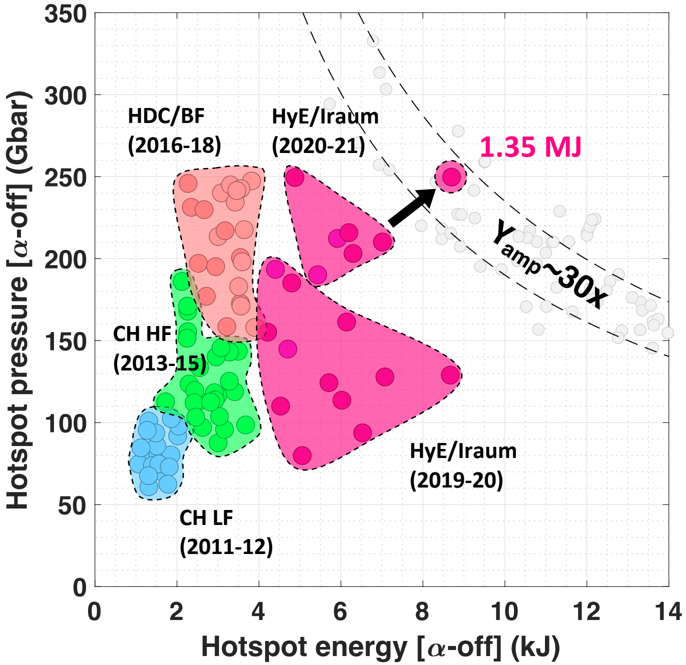


N210808 built on a decade+ of research and understanding

Lessons learned

- Low adiabat designs have yet to work as desired
  - Leading hypothesis is instability control at the fuel-ablator interface
  - Forces us to work at high adiabat which implies lower potential gain

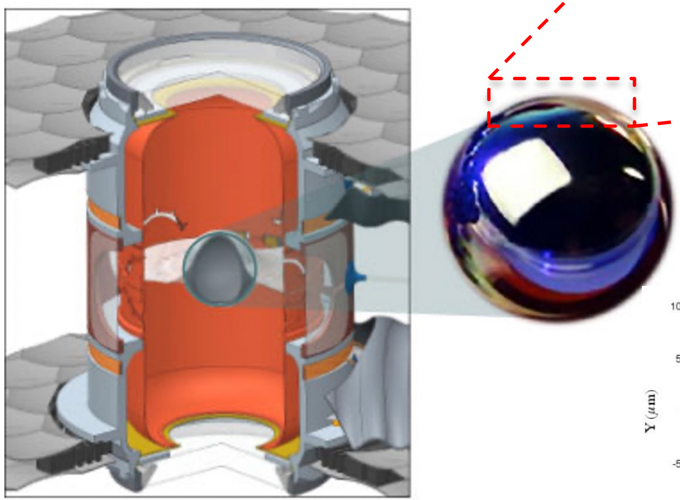
- High implosion velocity and low coast (extended duration of late-time x-ray drive) are very effective, if the implosion is not compromised by other degradations
  - More laser energy than NIF can presently deliver is highly desirable
  - "Advanced" hohlraum that can couple more energy to capsule, but also maintain low coast and symmetry control, also desirable

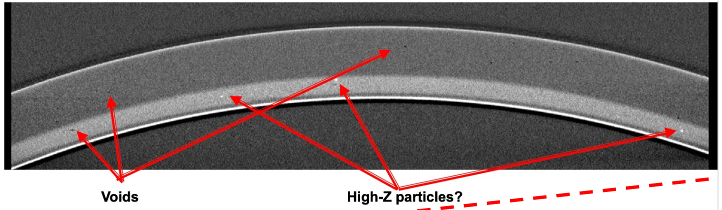
- Symmetry control has been very hard to manage
  - Symmetry of the shell (fuel + remaining ablator) areal density is the driving physical factor
  - Favors shorter laser pulses, low hohlraum gas fill (for LPI), and larger case-to-capsule ratio hohlraums

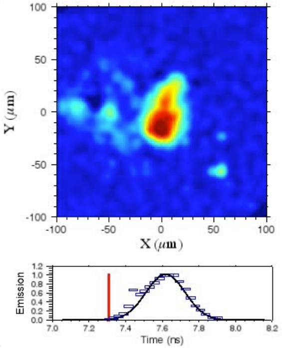
- Hydro instability and mix are manageable to a degree, but are still a limiting factor

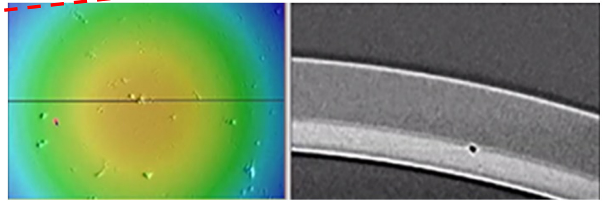
- Despite titanic efforts by the target and laser teams, target quality and laser delivery quality have ongoing issues

Targets are costly, complicated, fragile, and presently have many ICF performance limiting defects

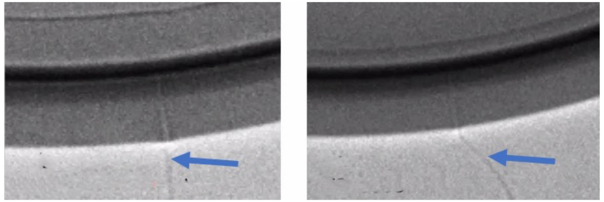








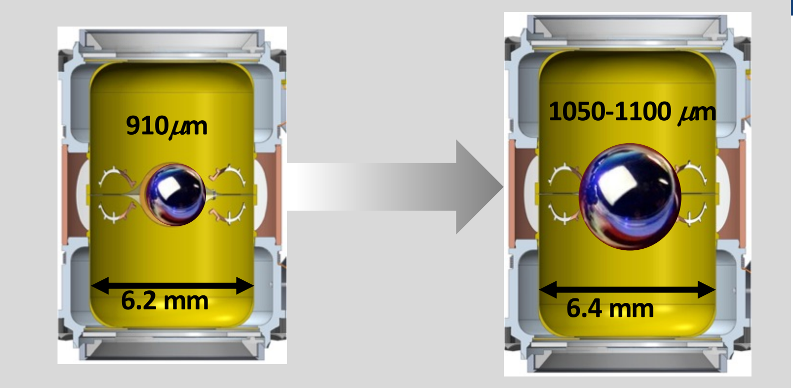
(Left) Confocal microscope image showing pits on the capsule surface. (Right) Tomographic image showing an internal void.



(Left) The five-micron fill tube used in the Feb. 7, 2021, experiment (an average human hair is about 70 microns in diameter). (Right) The two-micron tube used on Aug. 8. The thinner tubes are challenging to fabricate and extremely fragile, as shown by the bend that develops as the capsule cools.

HYBRID challenge: increase capsule scale, but keep similar adiabat, stability, velocity, "coast time", and *symmetry* with fixed laser energy

Much bigger capsule in to slightly larger hohlraum



HDC*[2] *(BigFoot[3])

Lead designer: L. Berzak Hopkins (C. Thomas)
Lead expt: S.Le Pape (D. Casey)

***HYBRID-E*[4]**

Lead designer: A. Kritcher
Lead expt: A. Zylstra

When brems ~ alpha-heating:

Yield — Ablation pressure "inflight" by lower "coast" — Scale

$$\underset{\text{Yield}}{Y} \sim p_{if}^{0.64} \frac{\overbrace{v_{imp}^{4.5}}^{\text{Implosion velocity}}}{\underbrace{\alpha_{if}^{1.4}}_{\text{Adiabat}}} S^{4.6} \underbrace{(1-\eta \cdot mf)^{0.93}}_{\text{Stability}} \overbrace{(1-nRKE)}^{\text{Symmetry}}{}^{3.8}$$

***High Yield Big Radius Implosion Design (HYBRID) strategy*[1]**

- With fixed laser energy higher efficiency hohlraums to maintain velocity
  - Much more difficult for symmetry (long pulse, smaller case to capsule ratio (CCR))
  - Use data-driven models[5] to guide design choices
  - Cross beam energy transfer in low gas fill hohlraums to control[6]

1: O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019)
2: S. Le Pape et al., Phys. Rev. Lett. 120, 245003 (2018)
3: D.T. Casey et al., Phys. Plasmas 25, 056308 (2018)
4: A.B. Zylstra et al., PRL 126, 025001 (2021); A.L. Kritcher et al., PoP 28, 072706 (2021)
5: D.A. Callahan et al., PoP 25, 056305 (2018); J. Ralph, et al., PoP, 25, 082701 (2018)
6: A. L. Kritcher, et al *Phys. Rev. E* 98, 053206 (2018) , L. Pickworth, et al, PoP (2020)

Similar to ITER strategy of increasing heating volume to surface loss ratio

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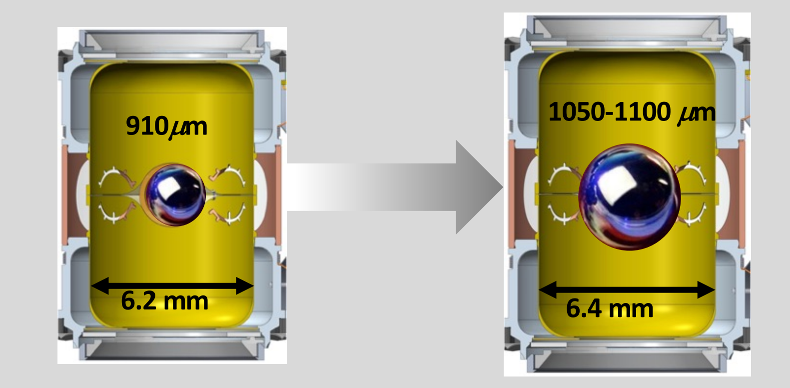
Much bigger capsule in to slightly larger hohlraum



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HYBRID-E[4]

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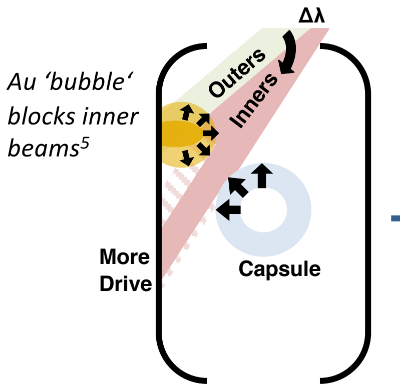
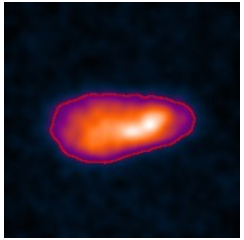
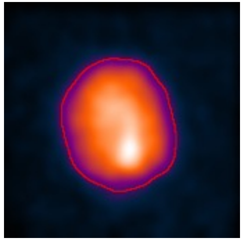
Symmetry control:



Δλ=0



Δλ=1A



Detuning the outer and inner wavelengths (Δλ) transfers power from outers to inners, increasing waist drive[4]

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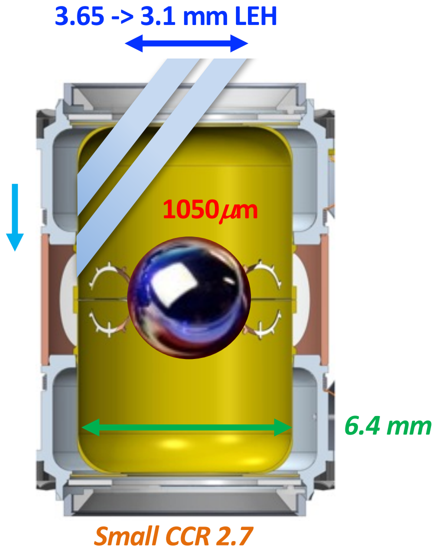
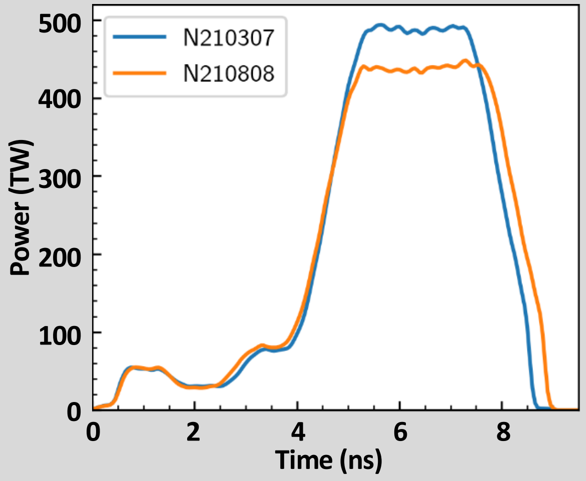
To push on coast[1,2] (more late-time x-ray drive) more we had to make the hohlraum even more efficient – smaller LEH, less rad loss

HYBRID-E design modified with smaller LEH[3]

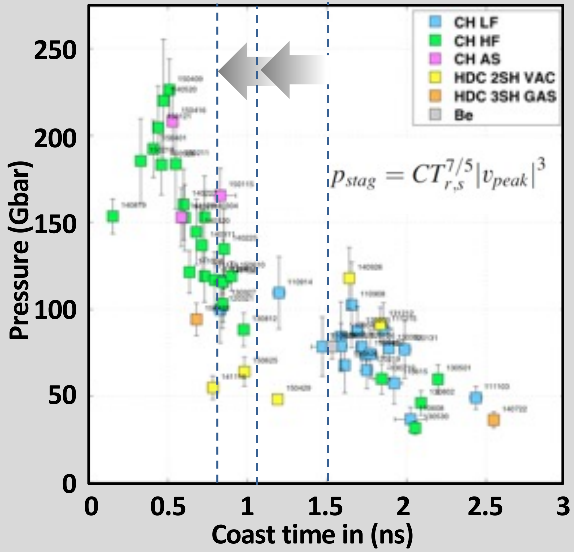


LEH = Laser Entrance Hole

With less rad loss laser power can be *lowered* and extended to decrease coast time



Allowed us to reduce coast another 350 ps in steep part of the curve[1,2]



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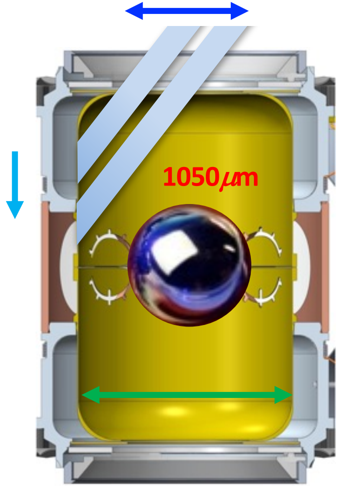

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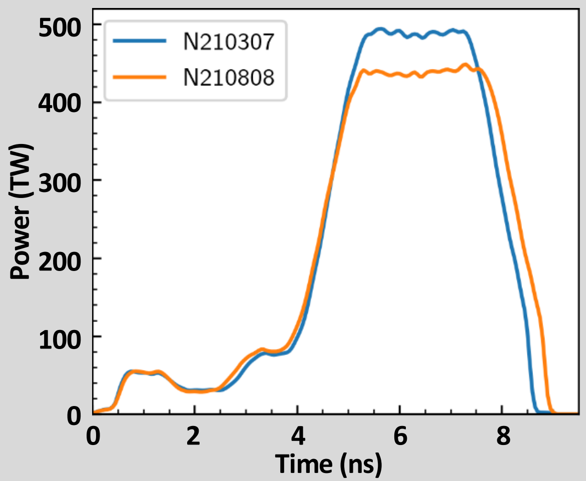

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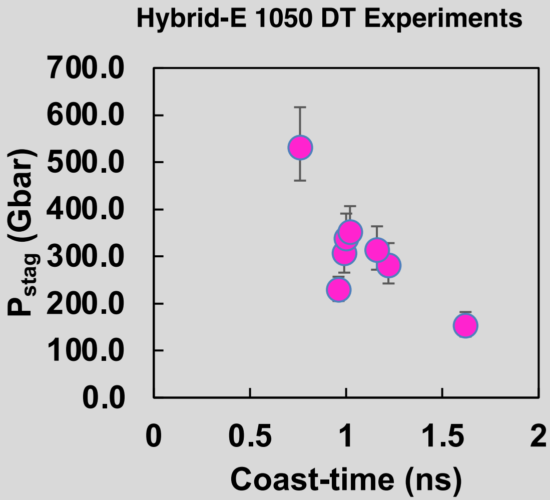

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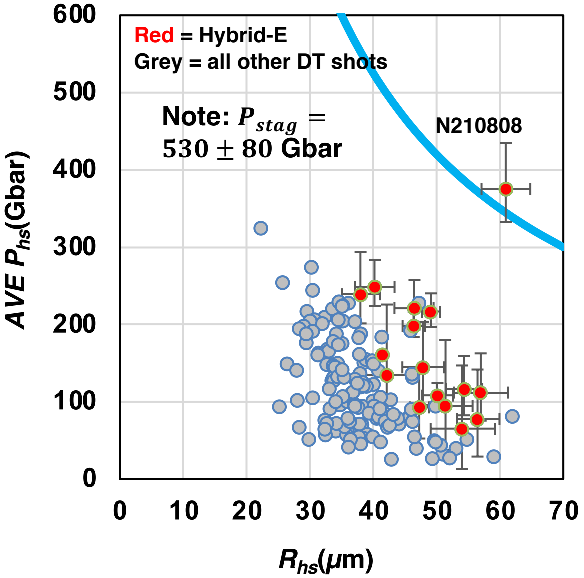
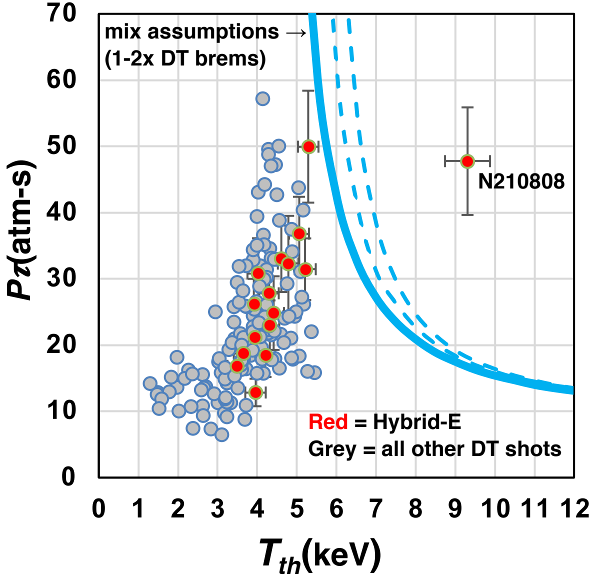
N210808 ignited (i.e. passed the tipping-point of thermodynamic instability) by many published metrics as the hot spot pressure and temperature increased

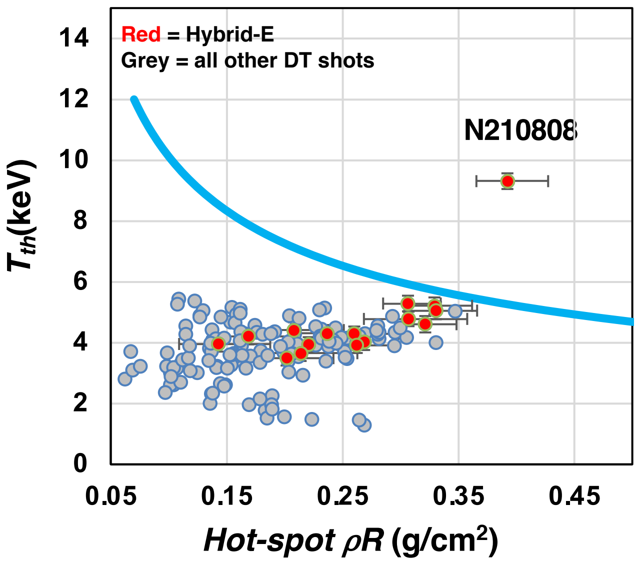
Metric: J.D. Lindl et al., Phys. Plasmas 25, 122704 (2018)



Metric: O.A. Hurricane et al., Phys. Plasmas 28, 022704 (2021)



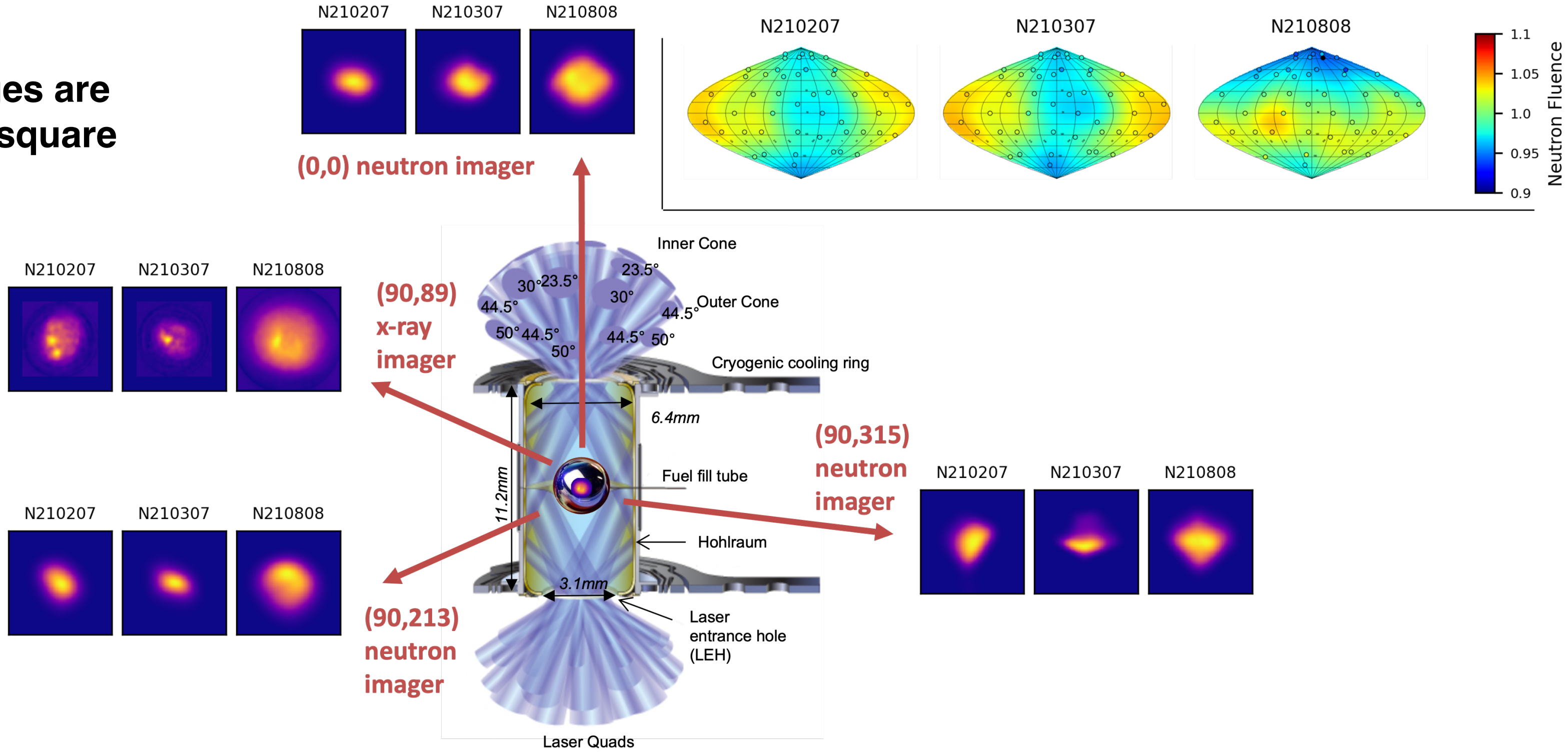
Tipton-Meldner, LLNL-TR-676592 (2015) burn on metric



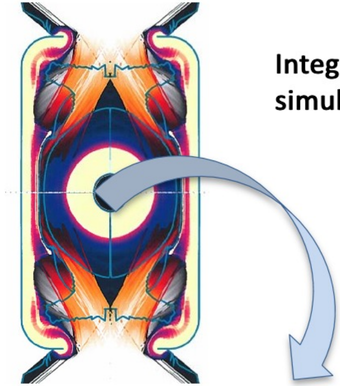
These metrics are different ways of estimating a Lawson-like ignition criteria for an implosion

Relative to earlier companion shots in the burning plasma regime, N210808 has better symmetry with a larger emission region

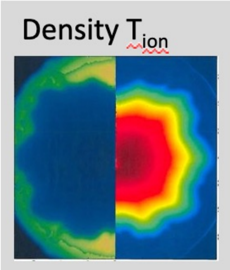
All images are 100 μm square

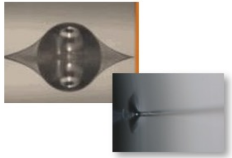


2D post-shot simulations capture many of the important implosion performance metrics in this new regime for this design



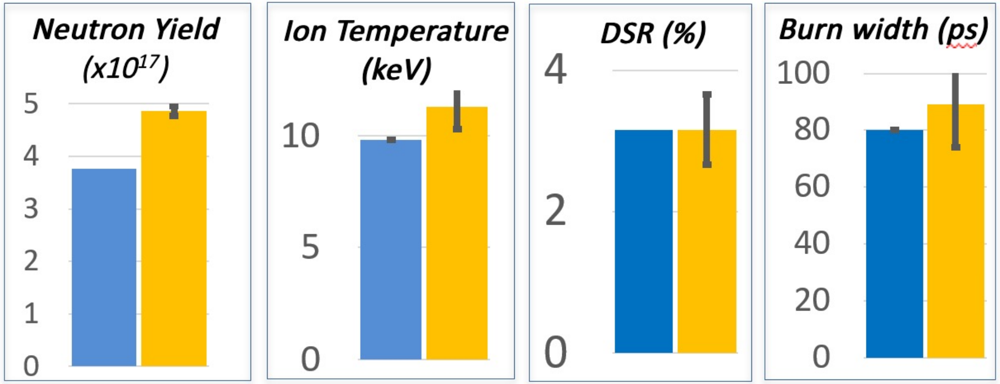
Integrated HYDRA simulations





Higher resolution capsule simulations

Model for degradations is benchmarked against predecessor shots



Simulated **Data**

- Consistent with high temperature, large burning hot spot
- Preshot predicted increase of 3x in neutron yield but below data (7.9x)
  - Postshot, including as delivered laser, 2 um fill tube, observed asymmetry, agrees to 20% in yield

A. Kritcher GO04.00002

N210808 is an “existence proof” that ignition in the laboratory is possible, but getting ignition has been extremely difficult

- N210808 is the first NIF shot to achieve $G_{capsule} > 5$, (Fusion energy/capsule absorbed energy)
- N210808 appears to meet several scientific definitions of ‘ignition’, defined as the tipping-point of thermodynamic instability, and obtained some burn propagation
- The shot achieved $G_{target} \approx 0.7$ (Fusion Energy/Laser Energy)
  - “Scientific Breakeven” when $G_{target} = 1$
  - Real Breakeven (more energy from fusion than what is consumed by facility) on NIF not possible, but NIF was not designed for energy production
- Lessons learned:
  - Symmetry control, stability control, and high compression all more difficult than originally envisioned
  - More sensitivity to target quality and laser delivery than originally envisioned
  - Higher energy has been more useful than high peak power
  - *Optimism is not a strategy*

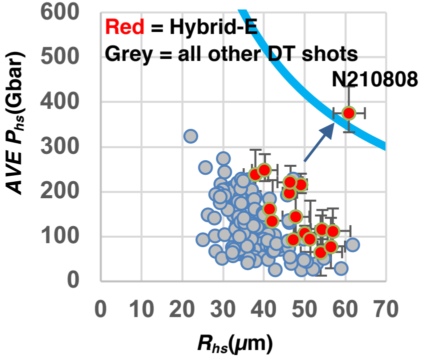
Data for N210808 as of Oct. 28, 2021

Some initial Data	
Capsule inner radius	1048.8 microns
HDC capsule mass	3927 ng
DT layer thickness	65.9 microns

Shot Data	
Y(13-15 MeV) neuts.	$4.34e17 \pm 1.17e16$
DT Tion	10.86 ± 0.37 keV
DD Tion	8.94 ± 0.4 keV
Te (range from channels)	$8.13 - 9.46$ keV
average DSR	3.01 ± 0.31 %
4 Pi DSR	3.3 ± 0.3 %
Burn width	89 ± 15 ns
Ave neutron P0 (radius)	55 ± 5 microns
Ave X-ray P0 (radius)	$77 \pm ?$ microns

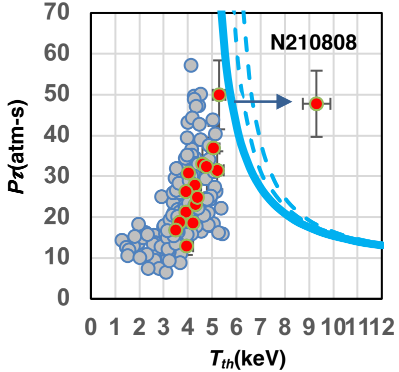
N210808 ignited (i.e. passed the tipping-point of thermodynamic instability) by many published metrics as the hot spot pressure and temperature increased

Metric: J.D. Lindl et al., Phys. Plasmas 25, 122704 (2018)



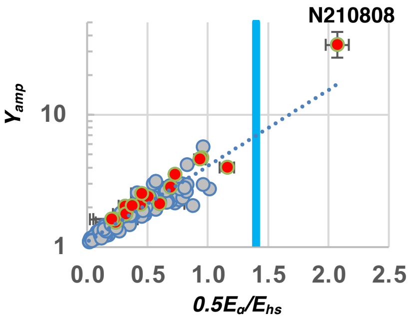
Pressure doubled

Metric: O.A. Hurricane et al., Phys. Plasmas 28, 022704 (2021)



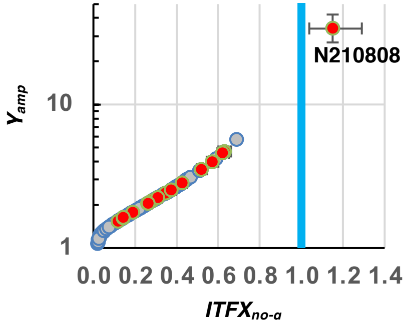
Temperature doubled

Metric: A.R. Christopherson et al., Phys. Plasmas 27, 052708 (2020)



Alpha-energy/hot-spot energy ratio doubled

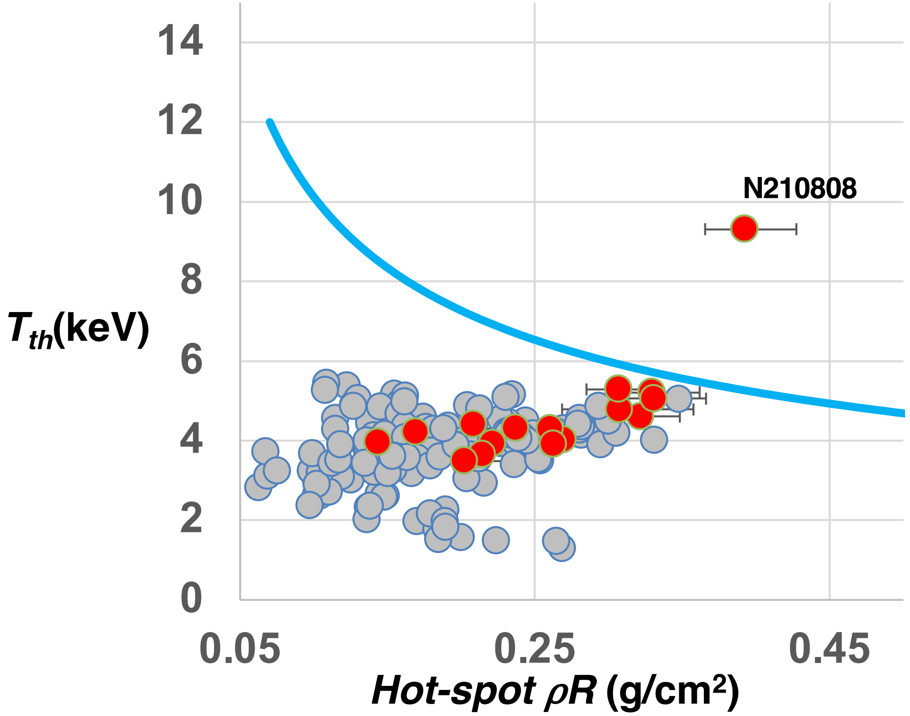
Metric: Patel et al., PoP (2020)



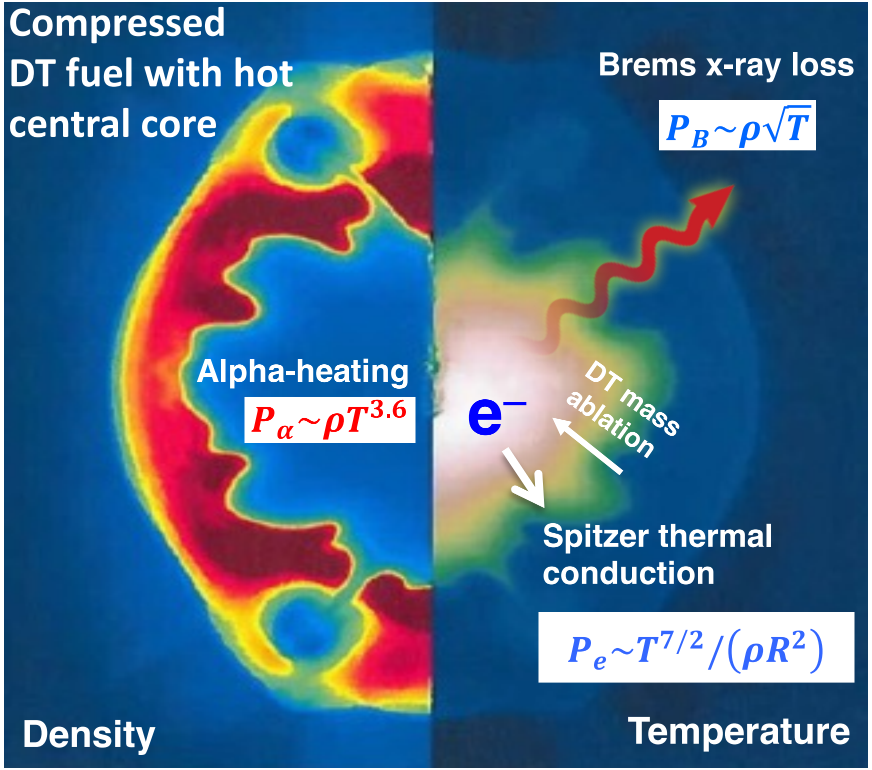
Ignition threshold experiment factor nearly doubled

These metrics are different ways of estimating a Lawson-like ignition criteria for an implosion

Tipton-Meldner, LLNL-TR-676592 (2015) burn on metric, which is slightly more conservative than B. Cheng, et. al. Nucl. Fusion 61, 096010 (2021) or Atzeni & Meyer-ter-Vehn (2004)



In order to get thermal instability (ignition), the plasma must have α-heating > all energy losses for a duration of time

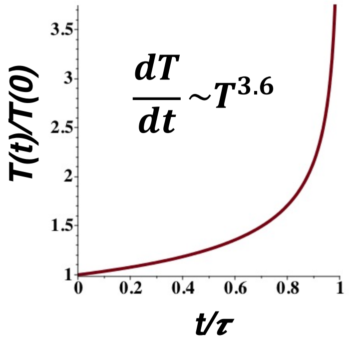


Time dependent heat balance (power/mass):

$$\underbrace{c_{DT}\frac{dT}{dt} = f_\alpha P_\alpha}_{\text{Ignition when these terms dominate}} - f_B P_B - P_e - \frac{1}{m} p \frac{dV}{dt}$$

Ignition when these terms dominate

Thermonuclear instability



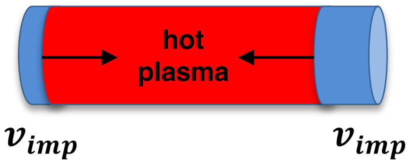
$\tau \sim 10's\ of\ picoseconds$

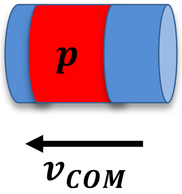
We are trying to engineer a situation where heating dominates over losses

Implosions resist compression in three ways: (1/3) asymmetry caused by non-uniformity of the shell and/or hohlraum x-ray drive

Asymmetric implosion abstracted to pistons: [Hurricane, et al., PoP, 2020; Casey, et al., PRL, 2021]

Mode-1:





Center-of-mass motion

From conservation of energy:

$$p = \frac{1}{3}\frac{m_{pistons} v_{imp}^2}{V}\left(1 - \frac{v_{com}^2}{v_{imp}^2}\right)$$

minimum hot volume (for V) **"wasted" KE**

$$f \equiv \frac{\rho\delta R_{max} - \rho\delta R_{min}}{\rho\delta R_{max} + \rho\delta R_{min}} = \frac{v_{hs}}{v_{imp}} \approx \sqrt{\frac{RKE}{0.66 \cdot KE}},$$

TABLE I. Spec on f with $a = 3.3$.

$\Delta Y/Y$	Max. f	Max. v_{p1} (km/s)
0.05	0.08	30
0.1	0.11	40
0.15	0.14	50
0.2	0.16	60

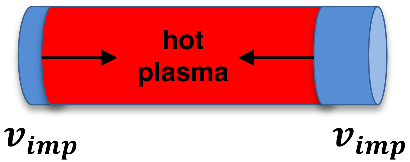
Experience:
23% probability shots in 8% spec
50% probability shots in 20% spec

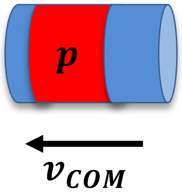
Wasted KE = residual kinetic energy (RKE) [Kritcher, et al, PoP, 2014]

Implosions resist compression in three ways: (1/3) asymmetry caused by non-uniformity of the shell and/or hohlraum x-ray drive

Asymmetric implosion abstracted to pistons:

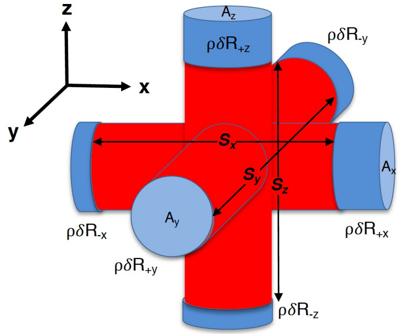
Mode-1:





Center-of-mass motion

Mode-2:



From conservation of energy:

$$p = \frac{1}{3}\frac{m_{pistons} v_{imp}^2}{V}\left(1 - \frac{v_{com}^2}{v_{imp}^2}\right)$$

minimum hot volume

"wasted" KE

Key parameter:

$$\rho\delta R_{WHM} = \frac{\sum A_j}{\sum \frac{A_j}{(\rho\delta R)_j}}$$

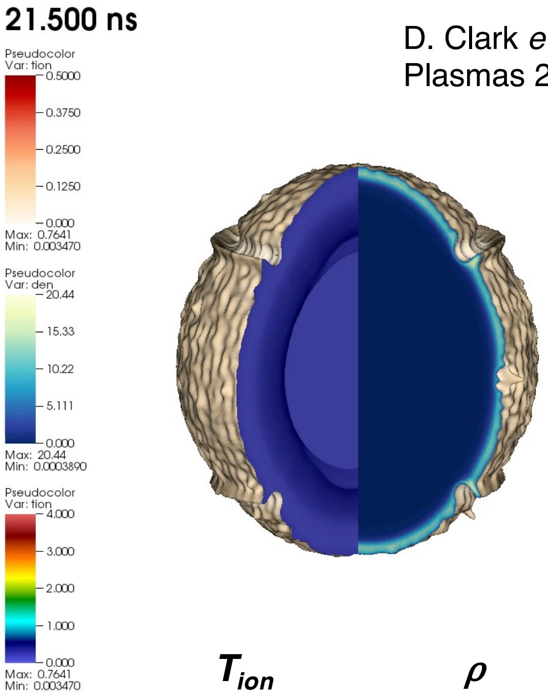
weighted harmonic mean of shell areal density

Implosions resist compression in three ways: (2/3) hydro-dynamic instability which defeats density and temperature gradients

"Takabe" formula for linear growth rate:

$$\gamma_{A-RT} \sim \sqrt{\frac{kg}{1 + kL_\rho}} - kv_{abl}$$

Numerous forms: e.g. Bodner, Betti, Kilkenny, Takabe, etc.



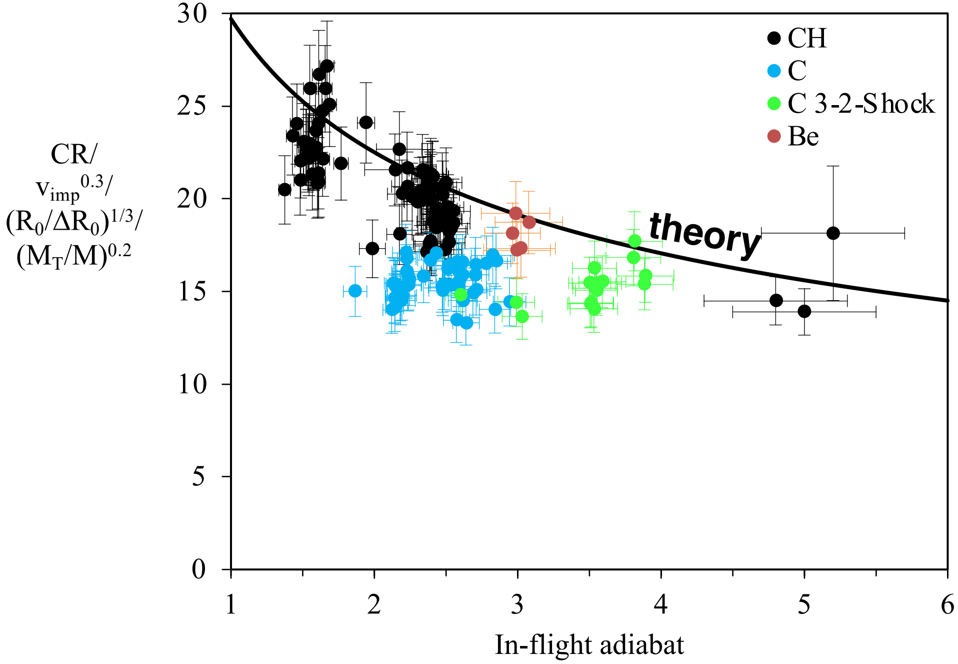
D. Clark *et al.*, Phys. Plasmas 23, 056302 (2016)

acceleration (*g*) is destabilizing (but how else to get high v_{imp}?)

long density gradients help
high ablation velocity (v_{abl}) helps

Implosions resist compression in three ways: (3/3) the materials involved appear stiffer than models expected

Measured compression



Expected compressibility based on entropy

Why?

Hypothesis:

-Ultra small-scale hydro-instability in crystalline ablators?

-Statistical mechanics derived equations of state (EOS) getting shock compression/rarefaction wrong?

-X-ray preheat?